# Estimating Soil Loss Rates for Soil Conservation Planning based on GIS in South Wollo Highlands of Ethiopia

JEMAL TEFERA [1], TAMIRAT WATO [2*]
[1]College of Social Science, Department of Geography and Environmental Studies,
Bonga University,
ETHIOPIA
[2]College of Agriculture and Natural Resource, Department of Plant Science,
Bonga University,
ETHOPIA

*Abstract:* - One of the key elements influencing Ethiopia's ability to sustain agricultural productivity is soil erosion. This study's goals are to assess soil conservation techniques in a watershed region with a dearth of data and predict soil erosion using the universal soil loss equation (RUSLE) model. To determine the RUSLE factors, soil information, rainfall, erosion control techniques, satellite pictures, and topographic maps were gathered. The terrain, vegetation, soil characteristics, and land use/cover are the factors that have the most impact on soil erosion. Five factors-R, the erosivity factor, K, the soil erodibility factor, LS, the topography component, C, the crop management factor, and P, the conservation support practice were multiplied to determine the average yearly soil losses. This study was carried out in the South Wollo highland, a region of the Blue Nile basin that experiences significant soil erosion. The region's undulating topography is a result of intense agricultural methods and poor soil conservation techniques. The annual soil loss predictions range between 0- and 240 tons $ha^{-1}$/yr. The total soil loss in the study area was 2,198,974 metric tons per year from 1,867,206.206 ha of the study area. The largest size among soil loss categories was that of 87-240 metric tons $ha^{-1}$/yr. The Southern and Center portions of the region have mild to extremely severe erosion risks, whereas the steep, intensively farmed northern parts have high to severe erosion risk zones.

*Keywords:* Watershed; sustainable management; Soil erosion; Revised Universal Soil Loss Equation; GIS.

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## 1. Introduction

The most important but most fragile natural resource in the world is soil [1-3]. One of the causes is soil erosion, a multidimensional and common global process of land degradation that lowers ecosystem services and functions [4-6]. Water-induced soil erosion accounts for the majority of soil deterioration on a global scale [7–10]. According to reports, soil erosion affects more than 2/3 of Africa [11]. 27 million hectares, or about 50% of the highland area, was extensively eroded, 14 million ha was seriously degraded, and more than 2 million ha was beyond reclamation, according to the Ethiopian Highland Reclamation Study Report [12].

Ineffective watershed management systems and poor land use practices are the main contributors to land degradation in Ethiopia [13], a major issue influencing crop output in the Southern region is considerable deforestation brought on by the demand for firewood and grazing on steep terrain [14], as well as inefficient management and resource usage [15].

There are numerous research papers about the danger of soil erosion at different spatial and temporal scales in Ethiopia's highlands [6, 14, 16-22]. All of the studies showed that erosion-caused land degradations are by far the biggest issues, causing soil fertility, water-holding capacity, and biodiversity loss [4, 23-25]. The size and scope, however, differ from region to region of the nation depending on farming practices, population pressure, the type and susceptibility of the soils to erosion, the local climate, the general topography, and changes in the agro-ecological setting of the area [26, 27].

All of this suggests that studies of soil erosion at particular locations are still important in Ethiopia for halting the problem of soil loss.

The current study was conducted in relatively unstudied but extremely vulnerable and delicate regions of the northwest highland watersheds, where soil erosion is a serious problem and a frequent occurrence. The region is more vulnerable to water-induced soil erosion and associated land degradation due to several causal factors, including, but not limited to, the inherent characteristics of the soil, improper land use/management practices, steep slopes, rough terrains, and complex ravine networks. To prevent additional harm, it is crucial to evaluate the rates of soil loss and identify regions that are vulnerable to erosion at such a remote location. Furthermore, precise, thorough, site-specific environmental data is needed for effective conservation planning and related land management methods. Therefore, the current study has been started to calculate the typical yearly soil loss rate and identify crucial places that are vulnerable to soil erosion so that the study may be properly intervened in utilizing RUSLE and GIS.

## 2. Materials and Methods

### 2.1. Study area description

The study was carried out in the South Wollo zone, North Eastern highlands of Ethiopia. It is one of the eleven administrative zones of the Amhara National Regional State. South Wollo zone is bordered on the south by North Shewa and the Oromia Region, on the West-by-West Gojjam, on the North-west by South Gondar, on the North-by-North Wollo, on the Northeast by Afar Region, and the East by the Oromia zone and Argoba special districts. It lies between latitudes of 10° 10’N and 11° 41’N and longitudes of 38° 28’E and 40° 5’E with elevation ranging from 1000 to 4200m above sea level (Fig. 1). The mean annual temperature and mean annual rainfall ranges from 14°c to 25°c and from 550 mm to 1200 mm, respectively [28]. According to previous studies [29–31], the region has a rough topography made up of very tall mountains, deeply cut canyons and gorges, valleys, and plateaus. Leptosols, Cambisols, Vertisols, Andosols, and Luvisols are the main soil types in Wollo regions [29]. Over 35% of the research area is covered by Leptosols, which are followed by Cambisols, Vertisols, Andosols, and Luvisols [29].

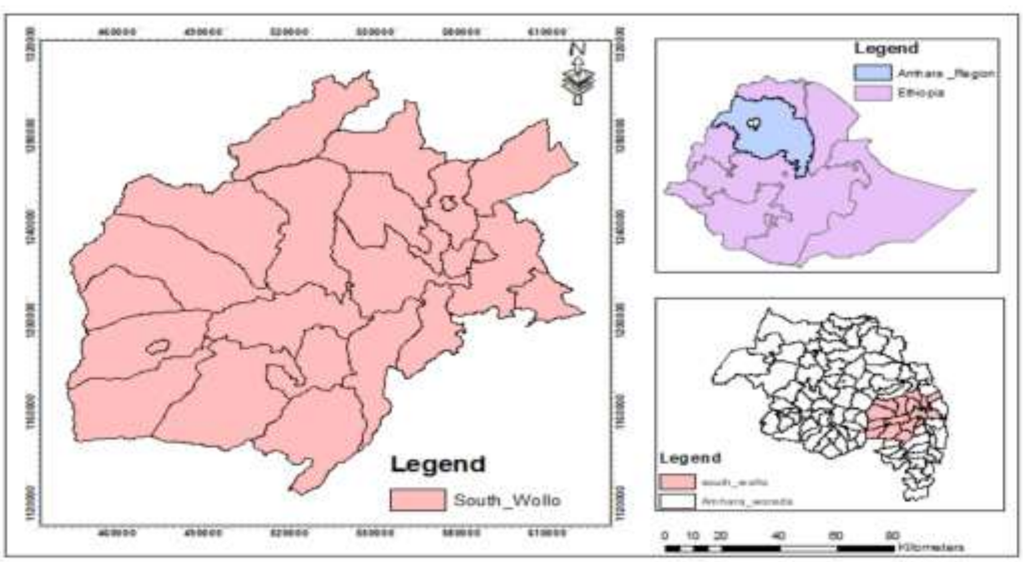


Fig. 1: Location Map of the Study Area

## 2.2. Data Sources and Methods
## 2.3.of Acquisition

Both primary and secondary data were used in the investigation. Four key tools were used to generate the primary data: focus groups, topographic maps, soil maps, and satellite imagery. Additionally, secondary sources are consulted, including statistics on the population and the climate. A terrain elevation model (TEM), which is used to calculate slope length (L) and slope steepness (S) parameters, is created using data on slope angle and length extracted from DEM and contour lines of varying heights. While a land use/cover map was created, crop management (C factor) and conservation practices (P factor) were determined using satellite data (land sat 8 images taken in February 2006 with path 181 and row 052). A field inspection was also conducted to locate any obscured features, observe crop management techniques, and confirm the final results of the land use. Rainfall data (1998-2012) from six stations (Mekane-Selam, Wegdi, Amba-Mariam, Worilu, Haik, Tossa) were collected from the respective meteorological station for computation of rainfall erosivity (R-factor) in the RUSLE. The majority of the RUSLE model's input variables were calculated using particular approaches or were taken directly from literature created expressly for the Ethiopian setting. The final map that shows the soil loss rate of the watersheds was created by merging the files created for each element that was taken into account by the RUSLE model in the GIS environment.

To estimate soil loss in a spatial domain, the required GIS data for the RUSLE were produced for each and integrated using a cell-by-cell grid modeling process in ArcGIS 10.8. Although the actual resolution (of the lowest resolution data source) is roughly 90m$^2$, each factor grid had a cell size of 30m. This resampling was carried out to include the improved precision of the topography and precipitation interpolations. All layers were projected with UTM Zone 37N using the WGS 1984 datum; these correspond to standards used by the Ethiopia Mapping Agency. The following methodology was used to generate the factor grids. Figure 2 shows the general framework followed.

**Table 1:** Data type, source, and description used in the study.

| Type of input data | Source of data | Description |
|---|---|---|
| ASTER DEM | USGS/EROS | 30 m resolution |
| land sat 8 | EGIA | 30*30 |
| Soil data | FAO | FAO–UNESCO–ISRIC soil classification system |
| Rainfall data | Ethiopian Meteorological Agency | Station and grid rainfall data for 31 years |

Source: Compiled by the Author, 2021

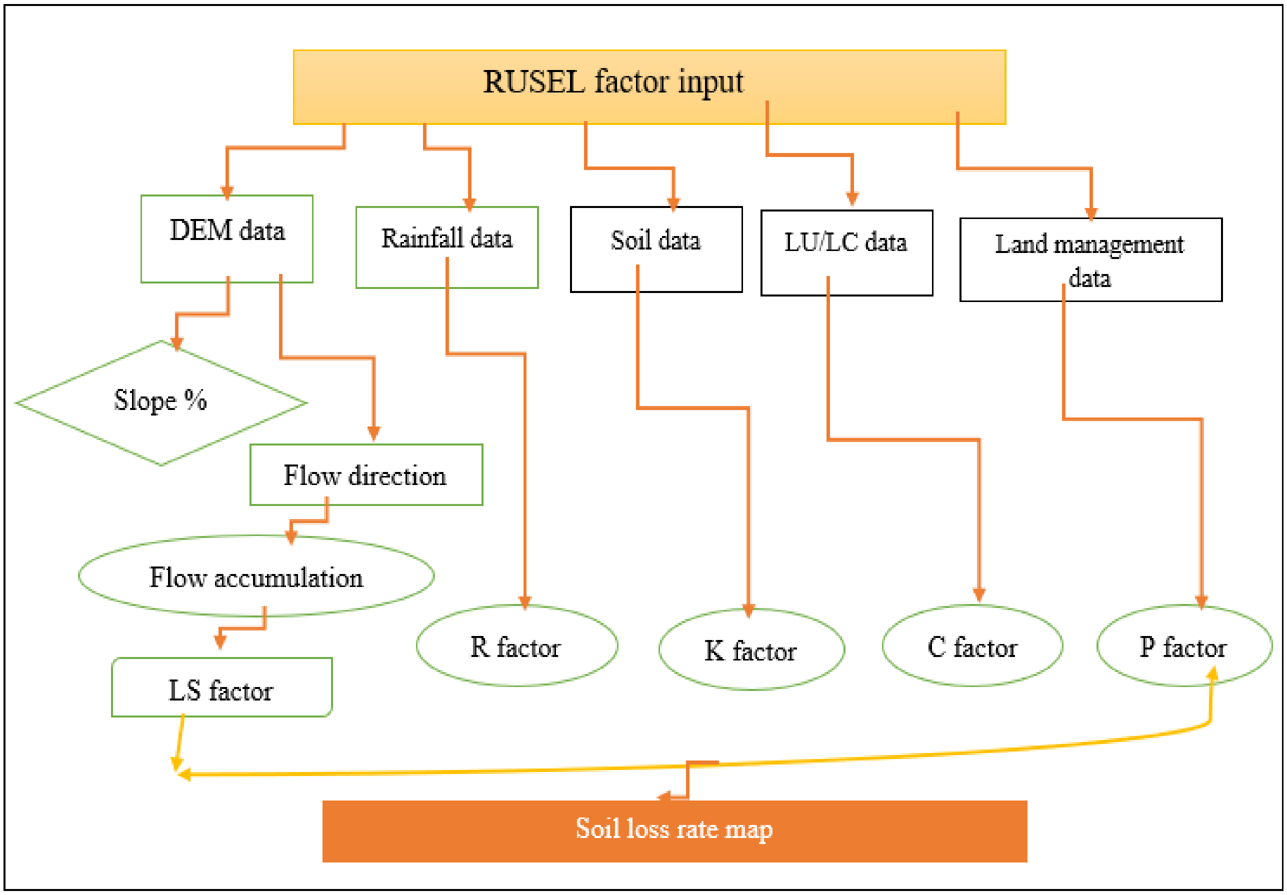


Fig. 2. RUSEL factor input

## 2.4. RUSLE model parameter description

To estimate annual mean soil erosion caused by rainfall, and identify the spatial pattern of the potential soil loss risks in the watershed, RUSLE model erosion input factors were structured in raster format of five multiplicative Eq. (1) [32] and given as follows:

$$A= LS* R* K* C* P \quad (1)$$

Where A is the annual soil loss (metric tons ha-1yr-1); R is the rainfall erosivity factor [MJ mm $h^{-1}$ $ha^{-1}$ $yr^{-1}$]; K is soil erodibility factor [metric tons $ha^{-1}$ MJ $^{-1}$ $mm^{-1}$]; LS = slope length factor (dimensionless); C is land cover and management factor (dimensionless, ranging between 0 and 1); and P is conservation practice factor (dimensionless).

### *2.4.1. Rainfall erosivity factor (R)*

Rainfall and soil loss are strongly associated, in part because of raindrops' ability to separate from soil surfaces and in part because rain contributes to runoff [33]. In this investigation, six rainfall stations that were randomly placed both inside and outside the study area (Table 2) were employed. The National Meteorological Agency gathered the monthly precipitation totals for these stations over 33 years. Monthly rainfall records from these six meteorological stations (Mekane-Selam, Wegdi, Amba-Mariam, Yeduha, Debre-

Work, Mertole-Mariam) covering the period 1985-2018 were used to calculate the rainfall erosivity Factor (R-value). The R factor is a complicated process that may be impacted by the quantity, length, intensity, energy, size, and pattern of the raindrops as well as the rate of the runoff that results [34]. In vrious research, this component has been found to have the greatest influence on soil erosion [35].

**Table 2:** Mean annual rainfall (31-year average) for 6 stations.

| Station | Annual rainfall (mm) |
|---|---|
| M/Selam | 891.92 |
| Wegdi | 886.69 |
| Tossa | 957.9 |
| Amba-Mariam | 1221.29 |
| Haike | 962.47 |
| Worilu | 1132.53 |

Source: National Meteorological Agency, 2018 (Computed)

The rainfall erosivity factor of the watersheds was calculated for this study using gridded rainfall data as well as observed average yearly precipitation (mm) data (converted from the daily average) collected by the six rainfall stations. According to [36], reliable estimates of rainfall erosivity must be derived from at least 15 years of data due to the considerable annual fluctuations in rainfall erosivity. As a result, numerous empirical formulae that estimate R- values from readily known rainfall totals have been devised [32, 37]. Hurni's empirical equation [37] was utilized in this study to estimate the R-value for the Ethiopian highlands based on annual total rainfall. It is specified as:

$$R= -8.12 + 0.562P \qquad (2)$$

In this study, the erosivity factor R was determined for Ethiopian conditions using the readily accessible mean annual rainfall (P) and the equation provided by [37], which was developed from a spatial regression analysis [38].

Rainfall in the highland regions is generally higher than in the plain of the lower watershed. The R factor was calculated using average long-term rainfall data interpolated from six locations while considering topographic variance. The R factor value ranges between 430 to 660 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$. The effect of rainfall on soil erosion is high in the upper part of the watersheds. On the other hand, the erosion potential of rainfall gradually decreases from the central plain to the lower part of the watersheds.

While rainfall has a greater impact on soil erosion in the northeastern, higher elevation portion of the zone, it gradually lessens from the middle plain to the northwest portion of the region.

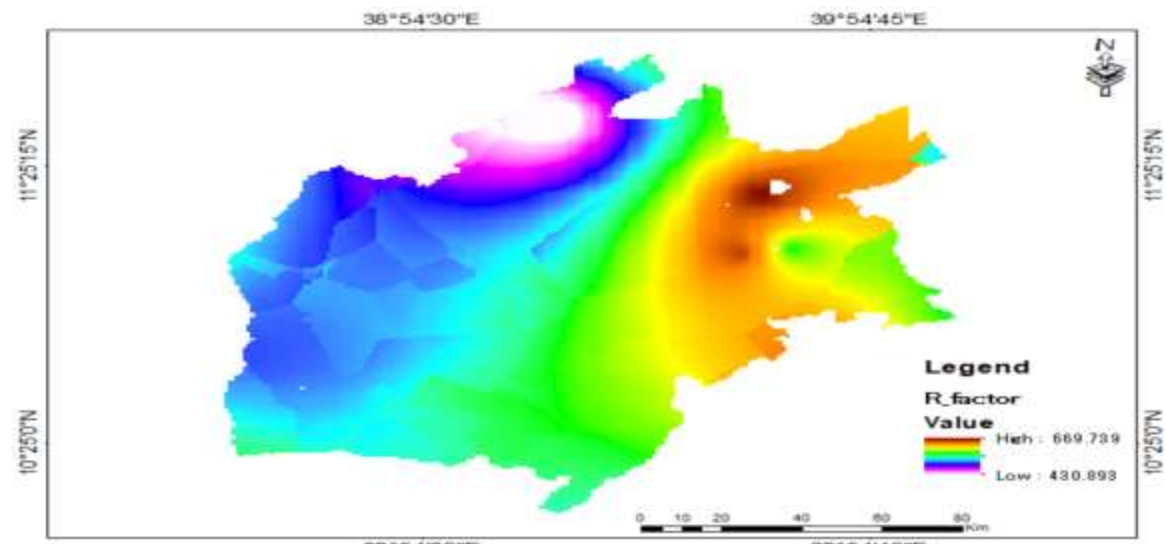


**Fig. 3:** Map of rainfall erosivity in the study area

### 2.4.2. Soil erodibility (K factor)

The K factor reflects the combined effect of soil properties, showing the general proneness of a particular soil type to erosion. In general, three types of soil classes were identified for the study area (Table 3). BE (Eutric Cambisols), QC (Cambic Arenosols) and Re (Eutric Gleysols). Erodibility depends essentially on the amount of organic matter in the soil, the texture of the soil especially sand of 100-2000 μ and silt of 2-100 μ, the profile, the structure of the surface horizon, and permeability [38]. The texture is the principal factor affecting K-values; structure, organic matter, and permeability are also important contributors [38]. In Africa, [38] have found K-values from 0.12 for ferralitic soils on granite, 0.2 for ferralitic soils on schist, and up to 0.4 if the ferralitic soils are covered by volcanic deposits of schist. They found 0.2-0.3 on tropical ferruginous soils, 0.01-0.1 on vertisols according to the World Soil resource based 2006 classification of [39], and 0.01-0.05 on soils, which were gravelly even on the surface. In this study, K- values estimated by the equation given by [37], derived from a spatial regression analysis [38] for Ethiopian conditions were assigned K-values (Table 3). Figure 3 shows the resulting K-values map. The erodibility map shows that Eutric Cambisols and Cambic Arenosols are highly susceptible to soil erosion, with K values of 0.064 and 0.059 respectively. Soils of the highlands such as Eutric Gleysols have moderate K values.

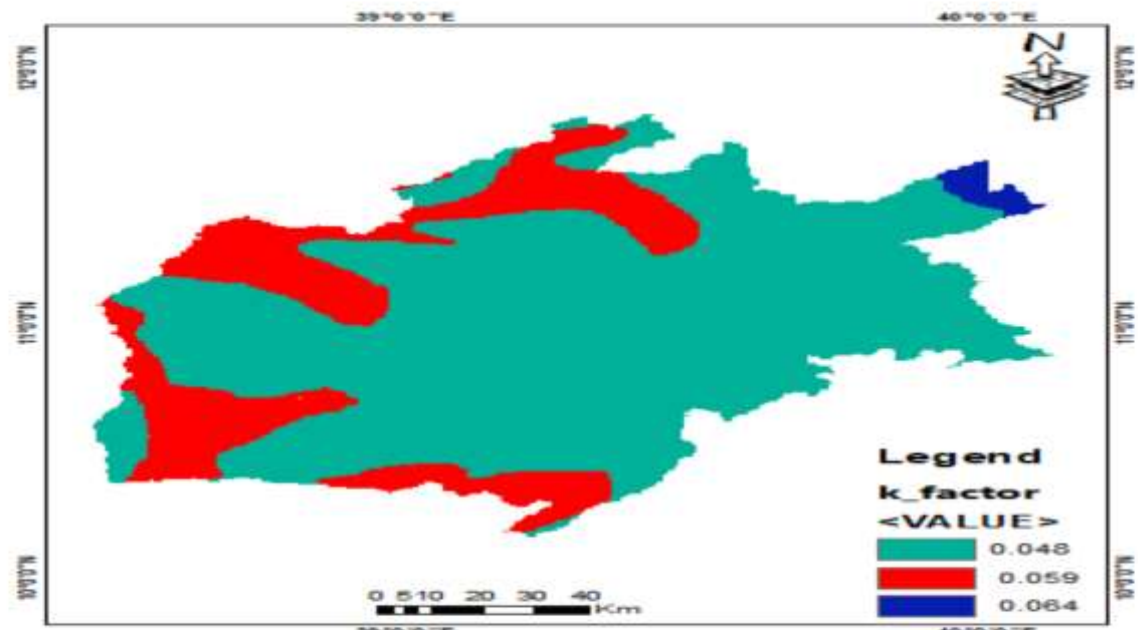


Fig. 4: Soil Erodibility map

**Table 3:** Soil unit of the study area.

| **Soil unit symbol** | sand % topsoil | silt % topsoil | clay % topsoil | OC % topsoil | Fc Sand | F organic | Fhi sand | fcl-si | K | k =Kusel*0.1317 |
|---|---|---|---|---|---|---|---|---|---|---|
| **BE** | 36.4 | 37.2 | 26.4 | 1.07 | 0.201 | 0.75 | 0.3 | 0.812 | 0.037 | 0.005 |
| **Qc** | 92 | 3.1 | 4.9 | 0.21 | 0.246 | 0.75 | 0.3 | 0.812 | 0.045 | 0.006 |
| **RE** | 68.3 | 3.1 | 16.6 | 0.5 | 0.201 | 1 | 0.3 | 0.812 | 0.049 | 0.006 |

Source: Adapted from [37]

### 2.4.3. Slope Length and Steepness (LS) factor

In the assessment of soil loss, the local topographic factor is the RUSLE parameter that is most vulnerable [32]. The LS factor, which tightly regulates soil particle transport, describes the combined effects of slope length (L) and slope gradient (S). With increasing slope length and gradient, the LS factor rose. The gradient that governs the flow velocity is denoted by the s-factor. The speed and erosive force of runoff will increase with the steepness of the land's slope [32, 35]. Every segment's total LS factor value was computed, and the results range from 0 to 298 (Fig. 5). The majority of the watershed's upper and central plains, which make up 78% of the research region, have low LS values (0–20). High LS values (20-298), which made up 12% of the study's total area, were primarily found in the watershed's higher, mountainous, and hilly portion as well as along the edges of the major streams.

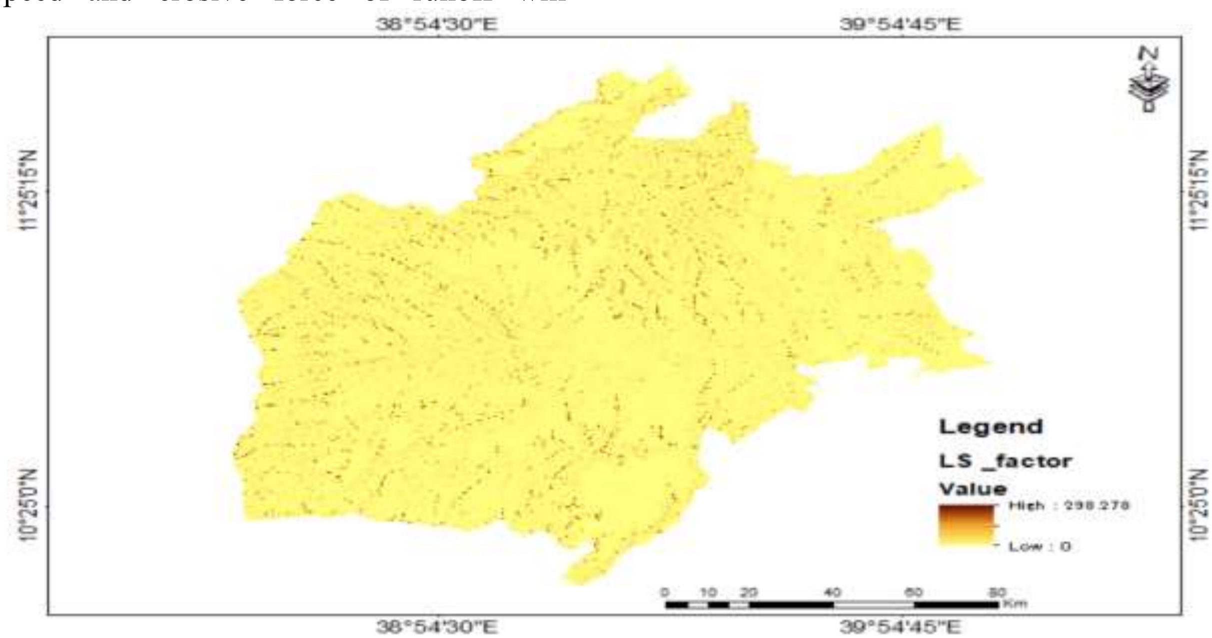


Fig. 5: LS factor map

#### 2.4.4. Crop cover and management (C factor)

The crop management factor is a measure of how much soil is lost throughout a certain crop as compared to the base soil. The effect of cropping and management techniques on the rate of soil erosion is reflected by the cover management factor (C-values) [32]. It is employed to assess the relative efficacy of crop and soil management techniques in halting soil erosion. The C- value is a ratio that contrasts the soil loss on land that is consistently fallow and tilled with the corresponding loss on land that is under a certain crop and management strategy. The C factor is dimensionless and ranges in value from 0 to 1. For the research area, which comprises primarily of agricultural fields, four typical land-cover groups were determined, as shown in Fig. 6. The mean C factor values for each record for a certain land use were then calculated using land-cover classes. To create the C-factor map seen in Table 4 and Figure 6, C values for farmland (0.15), forest and settlement (0.1), and barren land (1) were determined by [37].

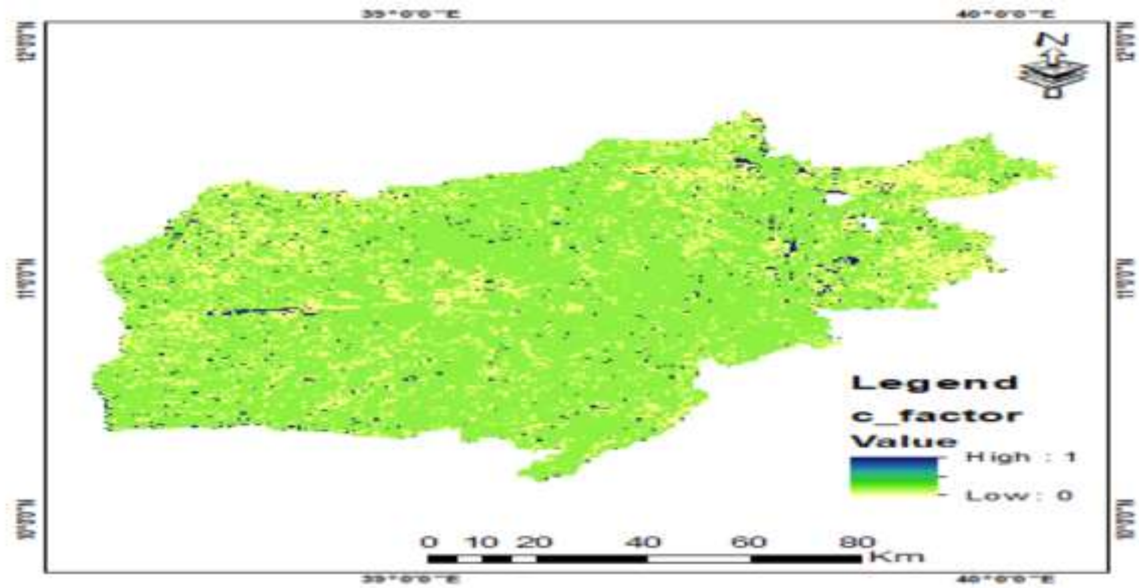


Fig. 6: C factor map

**Table 4:** Land use, area coverage, and cover management factor for the study area.

| LU/LC Categories | Area (%) | C –factor Value | Reference |
|---|---|---|---|
| Forest and settlement | 19.99 | 0.1 | [37] |
| Bare Land | 2.26 | 1 | [37] |
| Cropland | 77.76 | 0.15 | [37] |

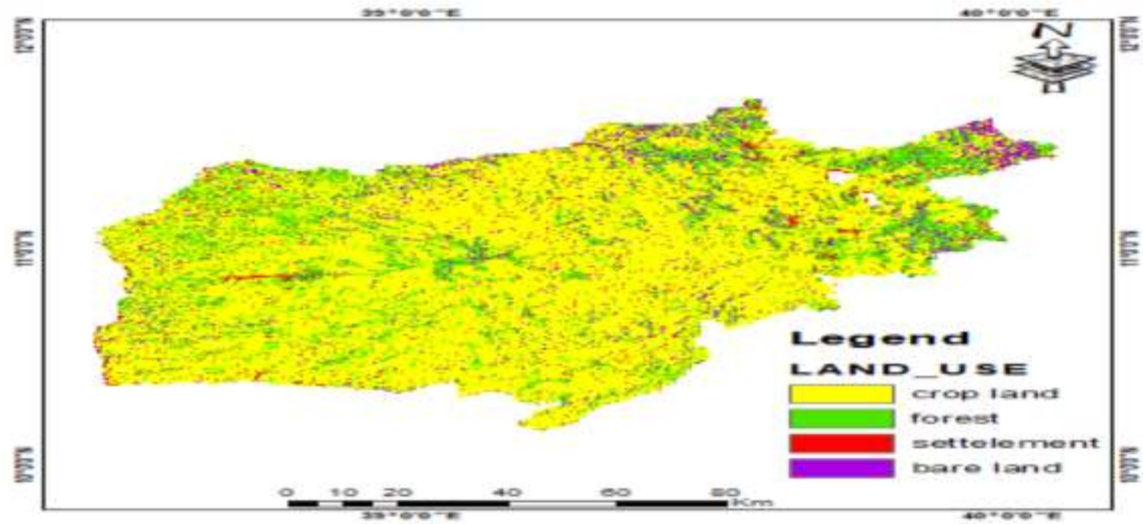


Fig. 7: Land use land cover map of the study area

**Table 5:** Land use land covers areal coverage.

| LULC | Area (ha) | Area (%) |
|---|---|---|
| Cropland | 1556510.303 | 80.46 |
| Forest | 181915.22275 | 11.67 |
| Bare land | 8865.45752 | 3.26 |
| Settlement | 101915.22275 | 4.6 |

### 2.4.5. Conservation practices practice (P factor)

The conservation practices component (p-values) accounts for the consequences of actions that will lessen the volume and pace of runoff and, consequently, the amount of erosion. For it to be quantified, mapping of preserved areas is necessary and depends on the type of conservation measures applied. According to the soil management techniques used on the particular plot of land, the P-value might range from 0 to 1. Only temporary terracing, strip cropping, mulching, and stone cover treatments in a small area are used to conserve soil or water in the research area. P values are determined by dividing the land into the land-use classifications of arable, settled, bare, and forest.

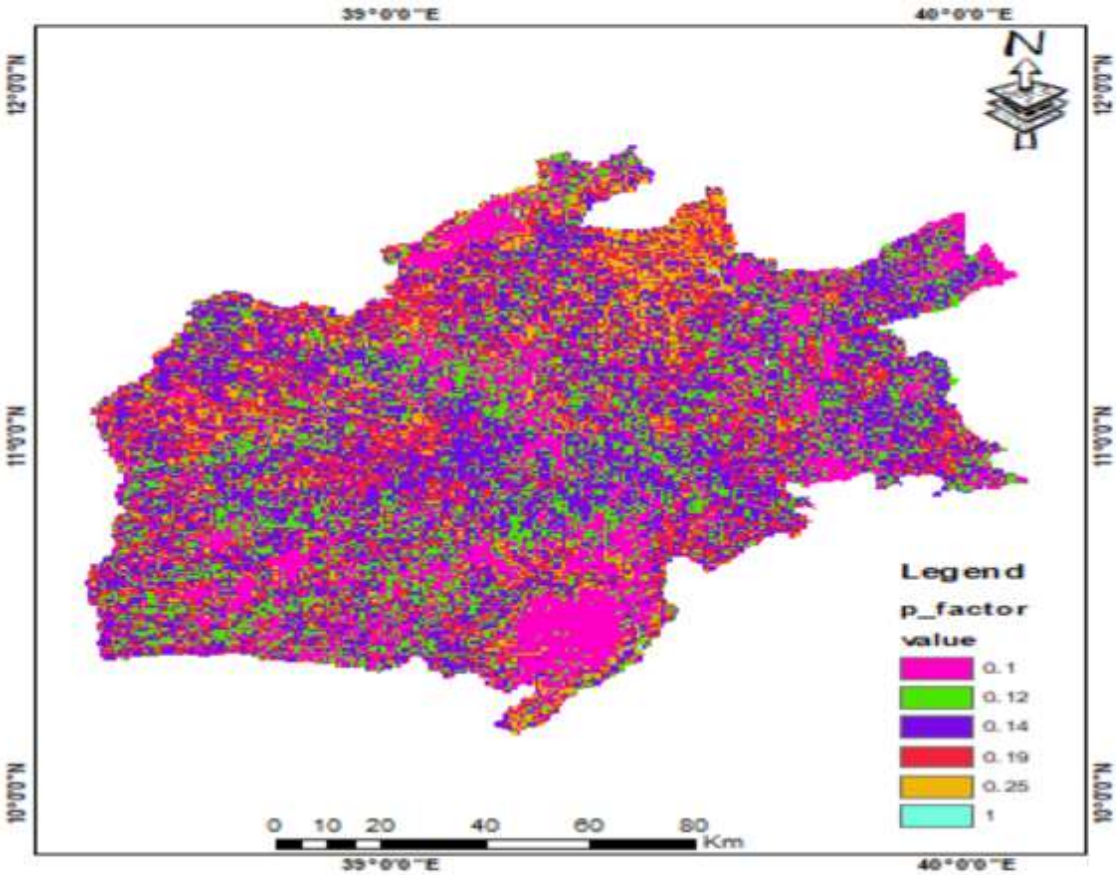


Fig. 8: Conservation practices (P-value) factor map

**Table 6:** Conservation practices factor (P-value).

| Land use | Slope category (%) | P factors | Reference |
|---|---|---|---|
| Cultivated land | 0_5 | 0.1 | [35] |
| | 5_10 | 0.12 | [37] |
| | 10_20 | 0.14 | [24] |
| | 20_30 | 0.19 | [22] |
| | 30_50 | 0.25 | |
| | 50_100 | 0.33 | |
| Other land use | All | 1 | |

# 3. Results and Discussion

## 3.1.Assessment of Soil Loss Rates

Using information on rainfall patterns, soil types, topography, conservation efforts, and management techniques, the empirically based RUSLE model can forecast the long-term average yearly rate of soil erosion on slopes. The computed annual values of soil loss of the watershed ranged from 0 in plain areas to well over 240 t $ha^{-1}year^{-1}$. In the lower reach degraded sloping areas, banks of streams, and at the specific spots of steep slopes of the watershed soil loss rate exceeds 2435 t $ha^{-1}year^{-1}$. The total soil loss in the study area was 2,198,974 metric tons per year from 1,867,206.206 ha. The largest size among soil loss categories was that of 87-240 metric tons $ha\text{-}^{1}yr\text{-}^{1}$ (Table 7). Table 7 showed that there are 334262.6 tons of soil loss from 1558510.3 ha, 807764.7 tons of soil loss from 161915.22 ha area, 494266.95 tons of soil loss from 141915.23 ha and 562679.75 tons of soil loss from 4865.46 ha/year. The presence of steep slopes, excessive agriculture, high rainfall, and overgrazing were observed in the downstream portions of the watersheds, which led to the discovery of severe to extremely severe erosion risk areas. Low erosion damage was seen in the watersheds' central region.

## 3.1. Prioritization for Soil Conservation Planning

The FAO's basic definition of desertification [41] was used to categorize various erosion potentials, with some modifications made to fit the research area's characteristics (Table 7). The term "soil loss tolerance" (SLT) refers to the highest degree of productivity and the greatest amount of permitted soil loss that may be sustained [29, 35, 42]. The usual SLT values vary from 5 to 11 tons $ha^{-1}yr^{-1}$ [32]; the range is determined by determining the amount of erosion that would be damaging to the soil. The steeper slope banks of streams, which collectively account for around 7.86% of the total area and 47% of the total soil loss, are the spatial locations of the places in the research area that are most severely affected by soil erosion, as shown in Table 7. In these locations, where erosion severity ranges from severe to extremely severe, first and second-order conservation priority are required. The research regions, which combined account for 37% of the overall soil loss and encompass 8.67% of the total area, also contain other areas with mild soil erosion. The rough topography and little vegetation in these locations contribute to the high rate of soil erosion there. The third conservation priority order is required because they frequently have moderate severity classes of moderate erosion potential land uses. The research region's plane or flat sections, which make up 83.46% of the total area and 16% of the total soil loss, appear to be the least susceptible to soil erosion in comparison to other places since they have a modest severity class, necessitating the use of the fourth conservation priority.

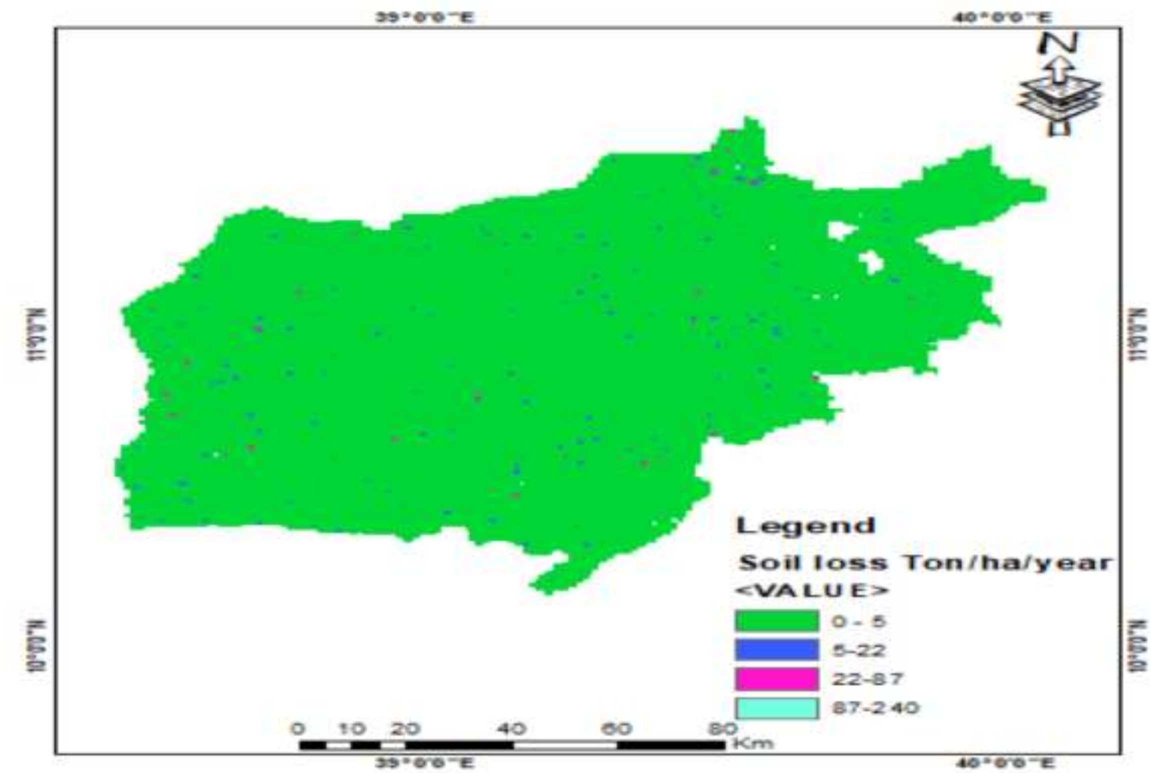


Fig. 9: Soil Loss rate map

**Table 7:** Annual soil loss rates and severity classes in the study area.

| Class | Soil loss (t ha$^{-1}$ yr$^{-1}$) | Description | Area (ha) | (%) | Annual soil loss (tons) |
|---|---|---|---|---|---|
| I | 0-5 | Slight | 1558510.303 | 83.46 | 334262.6 |
| II | 5-22 | Moderate | 161915.22275 | 8.67 | 807764.7 |
| III | 22-87 | Severe | 141915.22275 | 7.6 | 494266.95 |
| IV | >87-240 | Very severe | 4865.45752 | 0.26 | 562679.75 |
| | Total | | 1867206 | | 2198974 |

## 4. Conclusions

Several insights were gained from the modeling of soil erosion potential for the study region, including which area should be conserved first depending on the severity of soil loss and the interconnections between erosion components in a highland environment like that of Ethiopia. When there is a lack of data, remote sensing data and a GIS-based strategy are useful methods to estimate watershed-based soil loss rate. This study explains how to get the representative data required for the RUSLE and illustrates how it can be used to forecast soil loss and plan for soil conservation. The study's findings include a map of the zone's soil loss levels and a ranking of conservation priority sites. The watershed's yearly soil loss ranges from 0 to 240 t/ha/year. In the lower portions of the watersheds, extremely severe soil loss was seen at a rate that was higher than the acceptable soil loss limit. This was brought on by the slope's steepness and poor management techniques or a lack of supportive practices. Rill and sheet erosion are the most frequent types of erosion in the watershed, and they are caused by mountains with steep slopes, hillsides, and over-cultivation. Agricultural productivity may be threatened by this area of severe soil loss, which also extends its off-site effect of sedimentation on the nearby river banks. The primary influencing RUSLE parameter in the study region was the slope length and gradient (LS) component, which was followed by the Support Practice (P) element.

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**Data Availability**

The data presented in this study are available on request from the corresponding author.

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**Competing interest**

The authors declared that there is no conflict of interest in this scientific activity.

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